Journal of Cleaner Production 192 (2018) 354–363

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Comparative life cycle assessment of sludge management: A case study of Xiamen, China

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ARTICLE INFO

Article history:
Available online 21 April 2018

Keywords:
Wastewater treatment
Optimization model
Life cycle assessment
Sludge disposal
Sustainable management

ABSTRACT

Sludge management poses a great challenge to China's urbanization process as the number of wastewater treatment plants increases and the discharge standards are strengthened. China's sludge production rate is still low compared with developed countries but is undergoing a rapid growth due to increasing urbanization. Sludge management requires a systematic solution which integrates environmental effectiveness, social acceptability, and economic affordability based on a life cycle approach. In this study, we assess the environmental and economic performance of hydrothermal-pyrolysis technology (HPT), an emerging technology for sludge disposal. Climate change, human toxicity, costs, beneficial use of sludge and land occupation are used as indicators to compare HPT with conventional disposal methods, including incineration with two water contents, landfill, and compost. A particle swarm optimization (PSO) model based on the LCA results (PSO-LCA) was built to find a sustainable sludge management system in Xiamen. HPT was the most favorable scenario for sludge disposal overall, but given capacity restrictions and a trade-off between indicators, the optimal disposal proportion was for landfill to account for 9.3% of total sludge disposal, incineration with water content of 80% to account for 35.9%, HPT to account for 28.9% and compost to account for the remaining 25.9%. As further dewatering contributes a significant fraction to human toxicity effects and economic performance, the amount of dewatering should be selected based on the subsequent disposal process. The PSO-LCA method provides scientific evidence to inform decision makers to find a sustainable sludge management plan in accordance with wastewater features and socioeconomic conditions in Chinese cities.
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1. Introduction

Wastewater treatment plants (WWTP) are designed to minimize the environmental impact of discharging untreated water into natural water systems. Given the long-term need for ecological sustainability, the goals for wastewater treatment systems need to move to energy and resource saving, waste reduction and nutrients recycling (Pasqualino et al., 2009; Lin et al., 2014). Sewage sludge production and management have become a central component of WWTP after the major wastewater problem was solved (Peccia and Westerhoff, 2015), and efforts have been made to integrate sludge resource recovery with improvement of the sustainability of wastewater facilities (Guest et al., 2009). At present, methods of sewage sludge generation, treatment and disposal vary in different countries (Kelessidis and Stastinakis, 2012; Lin, 2009), and the continuous growth of sludge production has become a global challenge. Due to stricter legislation, which is continuously refining the requirements for the level of removal of various pollutants in treated water, the sludge generation rate is increasing, but growing environmental awareness among the public and pressure from environmental organizations has increased the perceived need to find economic and eco-friendly solutions to the sludge management problem (Ahmad et al., 2016).

The problem of sewage sludge is becoming increasingly acute in China and more investment in sludge treatment and disposal is urgently needed. In the initial development of China's WWTPs in the 1980s, attention mainly focused on fund raising, construction, wastewater treatment technology selection, and upgrading the

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https://doi.org/10.1016/j.jclepro.2018.04.171
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Abbreviations

WWTP	wastewater treatment plant
HPT	hydrothermal-pyrolysis technology
LCA	life cycle assessment
PSO	particle swarm optimization
CC	climate change
TA	terrestrial acidification
FE	freshwater eutrophication
OD	ozone depletion
HT	human toxicity
PMF	particulate matter formation
FF	fossil fuels
NPV	net present value
PB	payback period
DPB	discounted payback period
SPB	Static payback period

facilities. As no space was preserved for sludge treatment in the WWTPs the sludge problem has become increasingly serious, and has been exacerbated by rapid urbanization and industrialization during the last two decades. The number of WWTPs has increased remarkably during this period, leading to rapid sludge accumulation. Total sludge production in China had an average annual growth rate of 13% from 2007 to 2013, with 6.25 million tons of dry solids being produced in 2013, and this total is projected to reach 39.78 million tons in 2020 (Yang et al., 2015). In addition, the expansion of urban built-up areas means that many WWTPs, originally located in the suburban area or countryside, are now surrounded by residential areas. Public environmental awareness is increasing and higher income levels also lead to expectations of better living conditions. The odors produced by sludge dumping often provoke complaints and have become a new social problem. However, investment in sludge treatment and disposal (5.6 billion USD/year), is low compared to investment in wastewater treatment (68.8 billion USD/year), and the environmental benefits of wastewater treatment will be greatly diminished if the sludge is not treated well (Feng et al., 2015). More than 80% of sludge is currently disposed of by illegal dumping without any treatment (Yang et al., 2015). The organic content in Chinese sludge is about 37%, lower than the typical amount in developed countries, making anaerobic digestion less efficient, and the most commonly used disposal method is landfill and incineration after dewatering. Municipal waste management in China has shifted from landfill to incineration, but both methods have caused social conflicts due to citizen campaigns to block construction of nearby treatment plants and decreasing availability of landfill sites (Xiao et al., 2014). The conventional sludge treatment of landfill and co-incineration has thus encountered increasing pressures from local municipalities which are reluctant to receive more sludge. As a result, there is an urgent need to find an optimal solution for sludge treatment and disposal.

Hydrothermal treatment has recently been introduced to achieve deep dewatering of excess sludge (Agrafioti et al., 2013; Hii et al., 2014; Wang et al., 2017). Hydrothermal processing of raw sewage sludge essentially excludes the possibility of soil contamination, and the majority of organic matter is transformed into a simple, mineralized form (Cieslik et al., 2015). Pyrolysis is the thermal decomposition of materials in an inert atmosphere to produce vapors, which include condensable and non-condensable gases, liquids and a solid product (Samolada and Zabaniotou, 2014). A combined hydrothermal-pyrolysis technology (HPT) improves dewatering efficiency while also producing biochar, which is effective for soil amendment as it minimizes bioavailable As, Cr, Co, Ni, and Pb while increasing soil pH, total nitrogen, soil organic carbon and other nutrients (Muhammd et al., 2014; Sardar et all, 2013).

HPT has been operated as a pilot project in a WWTP in Xiamen for four years (Li et al., 2017), and while this method is technologically feasible, a detailed examination of the overall environmental and economic performance has not yet been conducted. The hydrothermal temperature is 180 °C, reaction pressure is 1.1 MPa, and carbonization temperature 500 °C. An energy penalty due to higher temperature and pressure will also influence the climate change effects, market-effects and policy making (Xiao et al., 2014), and so all of these are key issues that should be considered in the LCA (Sathre et al., 2012).

Due to the sludge characteristics and existing waste management pattern in China, the suitable technology for sludge treatment and disposal in Chinese cities remains uncertain, and there is an increasing demand for broader assessments covering the social and economic dimensions to ensure sustainability of sludge management (Fytili and Zabaniotou, 2008; Peccia and Westerhoff, 2015). Life cycle assessment (LCA) provides a scientific and technical tool to assess the impacts of new technologies to determine their propensity to consume resources and contribute to pollution, as well as their economic effects and social circumstances (Xiao et al., 2014). LCA was used in this research to identify and compare the environmental performance of the different scenarios based on existing sludge disposal facilities. A number of studies have focused on LCA for sludge management in different countries since 2002 (Suh and Rousseaux, 2002), and the environmental performance of sludge incineration has been widely reported (Abusoglu et al., 2017). The long-term fate of nutrient emissions after land application was also explored by Yoshida et al. (2018). However, multiple environmental impact categories are used in different scenarios, and the trends in various environmental effects produced by a single technology are often inconsistent. Sludge disposal technologies have different strengths and weaknesses in impact categories; for example, higher greenhouse gas emissions do not imply higher levels of human toxicity or land use (Hong et al., 2009; Abusoglu et al., 2017). These inconsistencies in environmental performance make it difficult to obtain comprehensive results that allow the combined effects of an individual sludge treatment technology to be assessed. It is difficult for policymakers to make a scientific sludge management plan, and allocate sludge treatment capacity among different technologies, especially for emerging countries with rapid sludge growth.

Climate change is a traditional impact category (Lundin et al., 2004; Soda et al., 2010; Liu et al., 2013). Comprehensive chemical characteristics (including toxicity characteristics and the effects on human health) are of the highest concern and have been taken into serious consideration in recent LCA sludge disposal studies (Cieslik et al., 2015; Silva et al., 2016; Yoshida et al., 2018). In addition, land use is a core issue in terms of public acceptance and increasing urbanization in China, so the land resource was also incorporated in our indicators. Based on previous research, we choose climate change, human toxicity, sludge treatment and disposal costs, and beneficial use of sludge as indicators to assess sludge disposal performance from a life cycle perspective.

The aim of the paper was to identify environmental and economic feasibility of HPT, and find the optimal sludge disposal proportion in terms of the environmental, economic and social effects. First, we assessed the performance of HPT, and then used LCA to compare this to conventional disposal methods, including incineration, landfill and compost. A particle swarm optimization (PSO) model with five indicators was used to construct a fitness function based on the LCA results, and an optimum model based on LCA results (PSO-LCA) was built for a sustainable sludge management in Chinese cities.

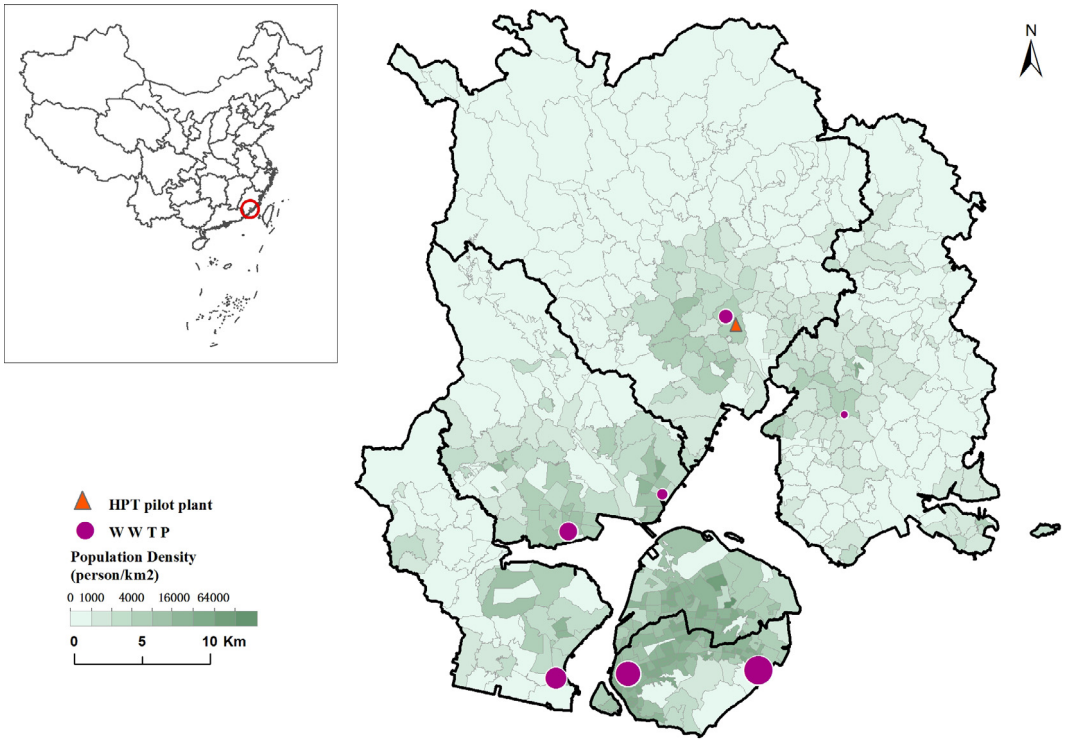

Fig. 1. Location of Xiamen city and the WWTPs.

2. Method

2.1. Research area

This research was conducted in Xiamen, a rapidly urbanizing coastal city in southeast China (Fig. 1) with a terrestrial area of 1699.39 km^2 and a resident population of 3.86 million in 2015. Since its establishment in the 1980s as one of five Special Economic Zones, Xiamen has undergone rapid economic development and urbanization. Real GDP per capita reached US$14646 in 2016, about 25 times higher than when the special Economic Zone was initially established in 1980. Over the last two decades, the urbanization rate has steadily increased from 38.5% to 80.5% (XSB, 2016).

At present, Xiamen has seven WWTPs and the total wastewater treatment, using a variety of treatment technologies including oxidation ditch, A2/O and bio-filter technologies, was 262 million tons in 2016 (Fig. 1). Discharged water from Xiamen WWTPs has achieved Class B of "Discharge standard of pollutants for municipal wastewater treatment plant" (GB18918-2002) in China since 2008. Types of sludge produced are shown in Fig. 2. WWTPs adopted two

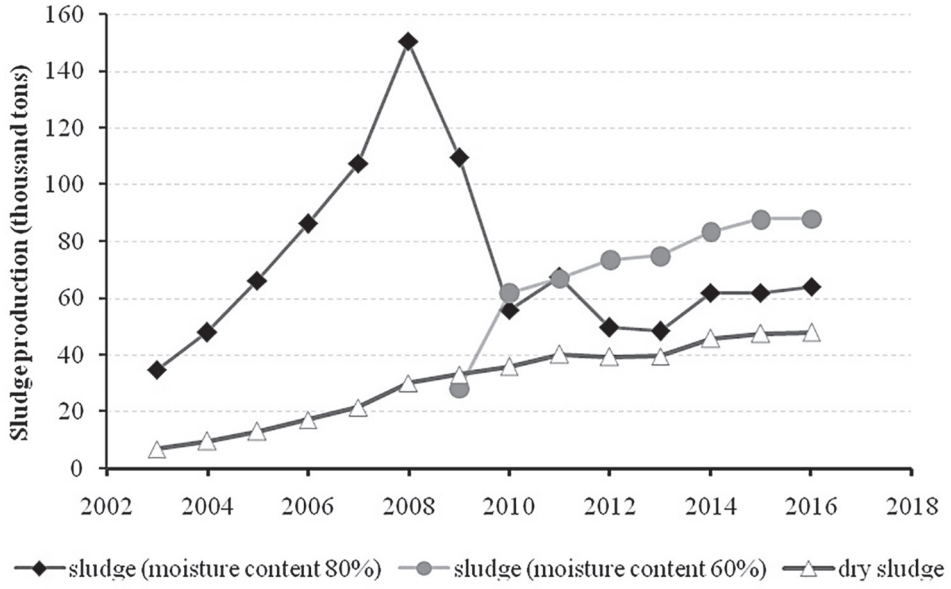

Fig. 2. Sludge production from 2008 to 2016 in Xiamen city.

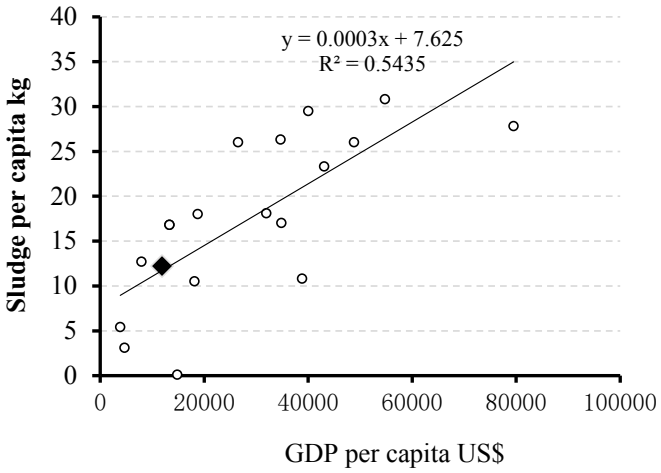

Fig. 3. GDP per capita and sludge production in the world.

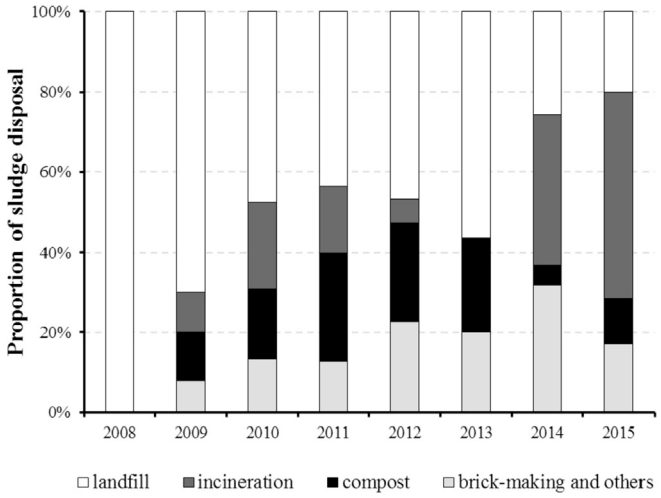

Fig. 4. Proportion of sludge disposal in Xiamen city.

dewatering processes: mechanical dewatering with centrifugal dewatering equipment, which enables water content reduction from 96% to around 80%, and plate-frame pressure filtration, combining mechanical dewatering and chemical methods, which enables water content reduction to below 60%. Typical levels of sludge production in developed countries are currently above 25 kg per capita per year (Fig. 3), but was just 12.2 kg per capita in 2016 in Xiamen (Fig. 3). Sludge production will likely increase in future as economic development continues and wastewater discharge standards improve to achieve emissions Class A according to GB18918-2002 (Fig. 4).

Purple circles present the sludge production by WWTPs; the larger the circle area, the larger the sludge amount.

Black dots represent sludge production in EU-27 (Eurostat, 2016), and the black square represents sludge production in Xiamen in 2016.

Until 2008 the only sludge disposal method in Xiamen was landfill, but since then the disposal of dewatered wet sludge has gradually diversified to include landfill, incineration, compost and brick-making. Although the sludge disposal rate in Xiamen is far higher than the national average, it still encounters some problems. Sludge disposal is the responsibility of municipal governments, and landfill and incineration plants are run by local municipal governments, so these two methods comprise the conventional treatment for sludge. Due to the increasing shortage of available land in Xiamen, the daily landfill processing capacity has exceeded the design capacity meanwhile incineration is opposed by the public due to perceived environmental risks, so Xiamen needs to find a more environmentally-friendly method to treat the increasing sludge quantities. While sludge can be used as a fertilizer after composting, the market recognition of the compost product is low due to the potential environmental risks (Liu, 2016), making it less competitive compared to ordinary fertilizer. Using sludge as a substitute for certain amounts of raw materials to produce brick or cement has been also proposed, but as a large amount of CaO is added to the sludge, there is a perception by consumers that the bricks lose strength over time due to reaction with CO_2. The brick-making industry is hardly to develop in the local market. As a result, the sludge disposal method has fluctuated and the city has not yet found a stable sludge management solution.

3. Life cycle assessment

3.1. Scope and inventory

The scope of LCA covers the environmental impacts and economic benefits of sludge treatment and disposal in five scenarios. The inputs include energy (e.g. electricity, steam) and material (e.g. water, flocculant), while the outputs include pollutant emissions and treated wastes (Table 1). HPT involved six processes including dewatering, hydrothermal treatment, mechanical separation, granulating and modeling, and pyrolysis carbonization. The

Table 1
HPT inventory data.

	Unit	Dewatering	Hydrothemal treatment	Mechanical separation	Granulating and modeling	Pyrolysis carbonization
Input						
Flocculant	kg	92.50	0	0	0	0
Biomass	kg	0	644.14	0	200.78	0.00
Electricity	kwh	0.23	27.17	13.55	6.81	20.36
Steam	KJ	0	927825	0.00	0.00	0.00
Output						
CO_2	kg	0	0	0	0	0.33
O_2	kg	0	0	0	0	0.72
SO_2	kg	0	0	0	0	0.52
NO_X	kg	0	0	0	0	0.22
Wastewater	t	0	0	39.38	0	0
COD	kg	0	0	1970.46	0	0
NH_4	kg	0	0	76.43	0	0
TN	kg	0	0	218.07	0	0
Biochar	kg	0	0	0.00	0	499.29

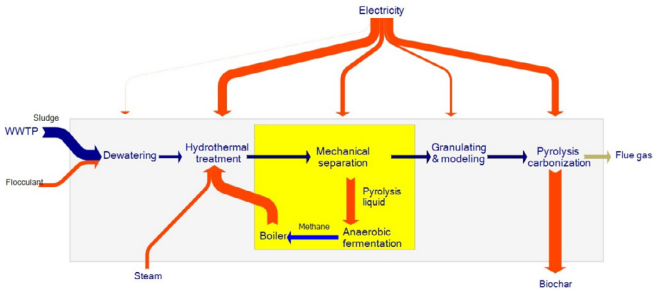

Fig. 5. Material flow of the HPT.

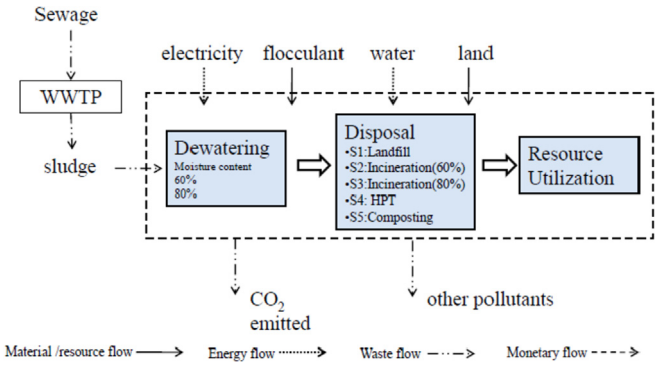

Fig. 6. System boundary of sludge treatment and disposal defined for the study.

material flow of the HPT is shown in the Sankey diagram (Fig. 5), where the width of the line indicates the size of the input and output.

To compare HPT with other sludge disposal methods, we set the parameters as follows. The data from Xiamen's WWTPs were used as the reference for the dewatering process. The water content of sludge from WWTP is 96%, falling to 80% or 60% after being dewatered. One ton of sludge with water content of 96% decreases to 0.17 t (including 15.8 kg of added CaO and 13.2 kg of $FeCl_3$) with water content of 60%. Adding 3.7 kg flocculant polyacrylamide into one ton of sludge with a water content of 96% reduces the water content to 80%, with sludge weight of 0.27 t. The inventory data for S1, S2, S3 were based on Ji et al. (2011), the data for S4 came from in-site measurement, and the data for S5 came from a field study in Xiamen. The cost data for S1, S2 and S3 were taken from Yao (2010). The benefits in S2 and S3 were electricity generated by the incineration process, with a feed-in-tariff of 0.65 yuan/kWh. The benefit in S5 was fertilizer with a price of 0.58 yuan/kg. Land occupation for all the scenarios was based on a field study and obtained from the Environment and Sanitary Department of Xiamen, which is responsible for waste management in the city. HPT data were collected through in-site measurement. The power-grid mix was assumed to be the same as the national electricity mix. Each input and output material and/or energy source for each scenario was quantified by LCA using Gabi 6.0 software, a professional tool which is commonly used for computer-based material and energy flow analysis (Bartzas and Komnitsas, 2017; Thinkstep, 2016). We first conducted a detailed LCA of HPT and then compared its economic and environmental performance with other conventional sludge disposal methods, including landfill, incineration and composting.

3.2. System boundary

In Xiamen, sludge with water content above 95% is usually sent to be dewatered by centrifugal dewatering and filter pressing. The functional unit used in this LCA is one dry ton of sludge. Our research first assessed HPT using LCA. Sludge with a water content above 60% is forbidden to landfillBased on the disposal method analysis in Xiamen city, five scenarios were compared: landfilling with water content of 60% (S1), incineration with water content of 60% (S2), incineration with water content of 80% (S3), HPT (S4) and compost (S5). The system boundaries of the five scenarios are shown in Fig. 6.

3.3. Environmental indicators

In this study, the environmental impacts for HPT were evaluated and quantified using the ReCiPe valuation system, which was the preferred methodology due to the wide range of potential impacts it covers (Lausselet et al., 2016). The method was based on a synthetization of CML2002 and Eco-indicator99 methodologies, which were jointly developed by Pre Company, Leiden University, Redboud University, and the Public Health and Environment Research Institution of the Netherlands. Our research concerned the following seven environmental categories: climate change (CC), terrestrial acidification (TA), freshwater eutrophication (FE), ozone depletion (OD), human toxicity (HT), particulate matter formation (PMF), and fossil fuels (FF).

3.4. Economic indicators

The economic indicators were net present value (NPV) and payback period (PB). NPV is commonly used to make first-time investment decisions (Adusumilli et al., 2016), as well as in capital budgeting to analyze the profitability of a projected investment, and was used here to determine the overall profitability. PB is the expected time period over which the initial cash outflow of an investment will be recovered from the cash inflows generated by the investment, and can be used as a measure of risk inherent in a project.

$$NPV = \sum_{1}^{n} \frac{CFt}{(1+r)^t} - C_0 \quad (1)$$

where n is the lifetime of the investment, C_0 is the initial investment cost, CF_t is the cash flow related to the generic tth year, and r is the discount rate.

In order to evaluate the discounted payback period (DPB), the change in the net present value (NPV) has to be examined to determine the point when a zero value is reached (Orioli and Gangi, 2017). Static payback period (SPB) does not take into account the time value of money; to counter this limitation, we used DPB to discount future cash inflows. The interest rate charged to Chinese commercial banks is around 4%. We also assess when the discounted rate is set to be 3% (deposit interest rate) and 8% (nominal GDP growth rate) respectively. Generally speaking, the lower a project's PB, the more desirable it is to undertake the project.

A sensitivity analysis was undertaken to determine the uncertainties of government subsidy and biochar price to the SPB, with the aim of evaluating the effects of the different supporting policies enacted by the government. The sensitivity coefficient was calculated as shown in equation (2):

$$E_i = \frac{\Delta SPB_i}{\Delta F_i} \quad (2)$$

where E_i is the sensitivity coefficient, F_i is the uncertainties factor, i is government subsidy or biochar price, and ΔSPB_i is the rate of change in SPB_i resulting from a change in F_i. A higher absolute value

of E_i indicates that SPB_i is more sensitive to the change in F_i.

To make a different economic comparison among five scenarios, we used the benefit-cost ratio (B/C) to indicate the economic trade-offs; when B/C is higher, the treatment is more economically feasible.

3.5. PSO algorithm

The PSO algorithm was proposed by Kennedy and Eberhart in 1995 as an evolutionary computation technology based on swarm intelligence, following observations of the foraging behavior of biological populations, such as bird flocking and fish schooling (Kennedy and Eberhart, 1995). Because particle swarm biological intelligence finds the optimum global structure through the interactions of individual particles, PSO is a reliable method in environmental and geographical research (Feng et al., 2011). The particle space is equivalent to a problem space in which each individual is a particle without volume and weight. In the initial state, each particle is located at a random position in the problem. Five indicators including climate change, human toxicity, benefit, cost and occupied land area were selected in the PSO model, which was implemented in Matlab (2016).

For each iteration, all particles maintain their own inertias, and adjust their flight speeds and directions according to the best local and global positions. Thus, individuals can self-organize into a small community, and then cluster to a larger community, which might then disperse into several smaller communities, with the aim of simulating the process of searching for the potential best solution in the problem space through evolutionary computation.

The fitness function F(w) is the objective function guiding the particle swarm detection process in the PSO algorithm. The fitness function can be constructed by calculating the environmental and economic performances of different treatments as follows:

$$F(w) = \sum_{i=1}^{5} x_{hi} w_i + \sum_{i=1}^{5} x_{ci} w_i + \sum_{i=1}^{5} x_{li} w_i + \sum_{i=1}^{5} x_{ei} w_i + \left(\sum_{i=1}^{5} x_{bi} w_i \right)^{-1} \quad (3)$$

where i represents the five sludge scenario and w_i is the proportion of scenario i, corresponding to a particle in the problem space. Five indicators were calculated in the last section. x_{hi} represents human toxicity for treatment i, and is determined by dioxins and heavy metals, expressed by 1,4DB (1, 4-dichlorobenzene). x_{ci} represents climate change impacts for scenario i, reflecting the potential influence of greenhouse gases produced per kWh of electricity, over a time period of 100 years (selected in accordance with the Kyoto Protocol in the sensitivity analysis). x_{li} represents land area for treatment i, x_{ei} represents economic cost, and x_{bi} represents benefits of byproducts for treatment i. The optimum position of a in the particle space, as determined by the PSO algorithm, would correspond to the minimum fitness value and be the best sludge disposal method in Xiamen.

Due to the impact on the optimization performance of the evolutionary algorithm parameters, a stepwise trial and error method was used to set the relevant parameters of the PSO module according to the literature (Kennedy and Eberhart, 1995; Liao et al., 2014; Trelea, 2003) and our experience.

4. Results

4.1. Life cycle assessment for HPT process

Characteristics of sludge from WWPTs in Xiamen are shown in Table 2. In this study, a pilot project with the capacity of 15 tons/day applied HTP in a WWTP.

Total electricity used for the process was 68 kWh**,** with **t**he six processes accounting for 0.33%, 39.89%, 19.89%, 10% and 29.89% of electricity use respectively.

Steam at a temperature of 200 °C was added at the hydrothermal treatment stage. After mechanical separation, the pyrolysis liquid produced methane through anaerobic fermentation to provide 927.8 MJ energy for the hydrothermal process. About 0.5 kg of biochar was generated in the HPT process for each functional unit. Climate change effects are the major environmental impact of HPT, followed by fossil fuels and human toxicity. HPT produced 1925 kg CO_2-eq and 43.5 kg 1,4DB for 1 ton dry sludge, and consumed about 504 kg oil-eq in disposal (Fig. 7). To reach the high temperature, exogenous heat must be introduced, making the CO_2 produced in the hydrothermal process the main contributor.

4.2. Life cycle cost of HPT

The cost in the dewatering process was 220 yuan/t, and dewatering comprised 16.2% of the total sludge treatment cost. The construction cost accounted for 15.1% of the total cost. The operational cost of HPT was 933 yuan/t, mainly from power consumption (54.8%), extra added materials (wood) (22.8%), labor costs (12.8%), steam (7.1%) and others (2.5%). After mechanical separation the pyrolysis liquid can provide a part of the heat source by anaerobic fermentation, so the cost of the external heat source is relatively low. Economic analysis was based on government subsidy for sludge disposal of 350 yuan/t and a biochar price of 400 yuan/t. The results show a HPT profit of 191.2 yuan/t.

The SPB for the sludge plant was 4.3 years. If the current bank deposit rate (3%) is used as the discount rate, the DPB of the sludge plant is 5 years; if the benchmark discount rate is set at 8%, then the DPB is 6 years, and NPV is 38.51 million yuan. This indicates that the DPB of this project is less than the target period of the project, and the NPV is relatively high. As a result, HPT is a profitable option for sludge disposal.

The effects of current government policies on the feasibility of HPT were also investigated. The sensitivity coefficient of the government subsidy to the payback period was 0.039, and that of biochar to the payback period was only 0.00175.

It can be seen from Table 3 that project viability is highly dependent on the government subsidy. When government subsidies are reduced by 40% and the price of sludge is 180 yuan/t, the project has some economic risks; when the government subsidies are reduced by 50%, the payback period is close to the life of the equipment. As the time value of the investment is taken into consideration, DPB shows that the project will bear more economic risks compared to SPB. The change in the price of biochar also has a

Table 2
Analysis of characteristics of raw sludge.

Proximate analysis/% (mass, ad)			Ultimate analysis/% (mass, daf)					HHVs/MJkg^{-1}
Ash	VM	FC	C	H	N	S	O	12.68
42.99	50.05	6.96	25.75	6.11	4.86	0.95	19.34	

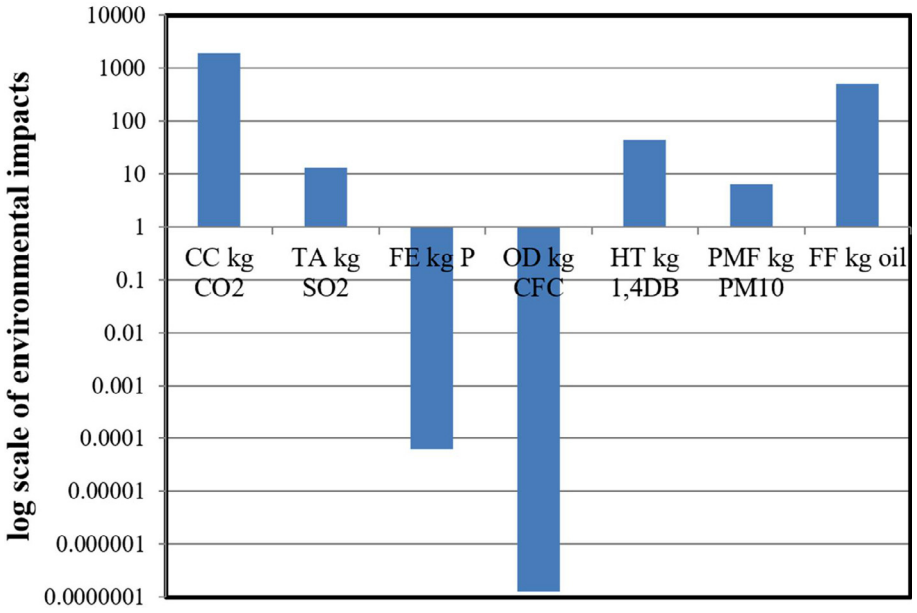

Fig. 7. Life cycle assessment of HPT.

corresponding influence on the project's economic viability. However, in the extreme case that biochar has no market price, the SPB is 5.4 years, still within the acceptable range. Even if the byproduct of HPT is regarded as a public good, HPT is still economically efficient during the lifetime of the investment.

4.3. Comparison of HPT with other sludge disposal techniques

CO_2-eq emissions were largest in S2 (Fig. 8) but lowest in S5. The amount of CO_2-eq produced in S4 was larger than that produced by compost. In addition, the impact on the environment caused by the dewatering process should not be overlooked. Plate-frame filtration and centrifugal dewatering are the most widely used sludge dewatering techniques, but the lower limit of the dewatering rate of mud cakes is only about 80%. When a plate and frame filter is used, and flocculent is added as conditioning, the lower limit usually reaches about 60%. Flocculant (CaO and $FeCl_3$) used in the dewatering process greatly improves the transportability and disposability of the sludge, but increases the treated sludge weight. Environmental emissions during flocculant production account for between 5.4% and 58.6% of total emissions in different disposal scenarios. The dewatering process in S1 and S2 make significant contribution to climate change effects. The contribution of transportation to climate change effects in S1 was less than 1%, while dewatering contributed 58.6% and landfill disposal 40%. The dewatering rate in S3, S4 and S5 was only 80%, so dewatering only accounted for 5.4%, 10.7% and 18.6% of total CO_2-eq emissions respectively in these three scenarios. In S2, the contributions of incineration and dewatering were 64.7% and 35.1% respectively, while the contribution of transportation to climate change effects was less than 0.5%. The recovery rate of energy during incineration was 11.8% and was insufficient to offset the climate change effects due to high resource consumption during the incineration process.

Dewatering was the major contributor to human toxicity in S1 and S2, because sludge dewatered by flocculants is more toxic than sludge treated by other methods. Although the human toxicity effect in the S2 disposal process was lower than in S3, S2 still resulted in the largest amount of toxicity due to the contribution of dewatering. Toxicity effects in S2, S4 and S5 were very low compared to other scenarios (Fig. 8).

Land occupied by S1 was the largest, followed by S5, while S4 occupied the smallest amount of land (only 4.4% of the land use in S1). Because rapid urbanization makes land resources scarce in most Chinese cities, S4 had the best prospects in this category.

S2 had the highest cost both in construction and operation (Fig. 8). The benefit/cost ratio in S4 was the highest, followed by S5 and S2. S1 had the lowest cost, but the benefit/cost ratio was 0 because the by-products did not have any market value, making its economic efficiency the lowest. The operation cost of HPT was

Table 3
Sensitivity analysis of government subsidies and biochar price.

Variables	Change				
	−10%	−20%	−30%	−40%	−50%
Subsidy (yuan/t)	270	240	210	180	150
SPB (year)	5.10	6.27	8.12	11.55	19.96
Biochar (yuan/t)	360	320	280	240	200
SPB (year)	4.37	4.44	4.52	4.60	4.68

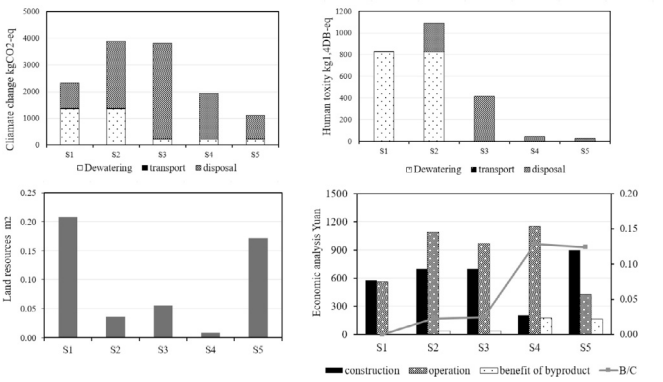

Fig. 8. LCA comparison of different scenarios. S1:landfilling with water content of 60%; S2: incineration with water content of 60%; S3:incineration with water content of 80%; S4: HPT; S5: compost.

highest compared to other disposal methods. However, because HPT is an emerging technology there is a high possibility of finding alternative residue instead of electricity and wood to reduce the operation cost in future.

5. Optimization of sludge disposal methods

Among the optimization parameters, the number of swarm particles was set to 100, the inertia weight ω used to balance global and local search capabilities was set to 0.8, and the learning factors c1 and c2 (representing the stochastic acceleration weights of each particle which will pull particles to the position of the global best particle and local best particle) were set at 2.8 and 1.3 respectively. The maximum velocity of each particle (a constraint to control the global exploration capabilities of the particle swarm) was set to 0.3, and the maximum iteration of the PSO algorithm was set to 2000.

Using the restricted conditions from equation (3), the best ratio of S1, S2, S3, S4 and S5 to be used as calculated by the PSO algorithm approach was 0:0:0:1:0. Taking all environmental, economic and social aspects into consideration, HPT had the best performance because it minimized land resource consumption and had less negative impacts on human health and the environment. Biochar had some advantages from the perspective of sludge product value. The NPV and the PB were within the acceptable range. This scenario therefore had the best economic benefits compared with other sludge disposal technologies commonly used in cities. Leaving aside the effects of HPT, the best ratio of S1, S2, S3 and S5 was 0:0:0:1. S5 had the second-best performance in the PSO analysis. The overall ranking of the five technologies based on the PSO was S4 followed by S5, S3 and S1, with S2 last place.

Due to path dependence, the actual urban capacity for sludge disposal imposes further constraints. For example, the proportion of sludge recycled to agriculture is expected to remain almost constant (42% increasing to 44%) between 2010 and 2020 in the EU (Samolada and Zabaniotou, 2014). As a new technology without previous disposal capacity, HPT capacity in Xiamen is limited to a maximum of 40% of total sludge disposal. With these constraints, and taking the sample data as an example, the optimization module began to converge at iteration 600 and achieved a global optimum fitness function value of 430.57. Eventually, the optimal proportion of sludge processed by S1, S2, S3, S4 and S5 in urban areas was determined to be 9.3%, 0, 35.9%, 28.9% and 25.9% respectively. In terms of land occupation, compost is second only to landfill, but emissions are minimal in climate change and human toxicity. HPT is second only to compost in terms of climate change and human toxicity, and is best for land use. The waste-to-resource technologies (HPT and compost) are expected to be the major disposal method in future, followed by incineration. The landfill proportion should decrease due to the trade-off between social, economic and environmental indicators makes it less attractive.

Sludge incineration has the highest costs and climate change effect due to the large amount of energy consumed, resulting in a reduction in its proportion in the future, but still the largest proportion of the five scenarios. In December 2016, China released the "13th National Urban Wastewater Treatment and Recycling Facilities Planning", which sets forth the technical requirements for sludge disposal. The sludge disposal facilities should be constructed in accordance with the principle of "combining centralized and dispersing treatment technology" to create a scale effect and encourage resource recycling. The result is also consistent with the national policy guidance.

6. Conclusion

Sludge management poses a great challenge to China's urbanizing cities. The life cycle assessment (LCA) results showed that HPT produced 1935 kg CO_2-eq for 1 dry ton sludge, and the discounted payback period was 6 years. Although HPT is dependent on government subsidies, it is still economically efficient during the lifetime of the investment. As an emerging technology, there is still high possibility to find an alternative residue as a heating source and to reduce the use of external fuel to further reduce the operating cost. Compared with conventional treatments, including incineration with two water contents, landfill, and compost, HPT showed overall benefits taking into account the trade-offs between environmental effectiveness, social acceptability, and economic affordability. Based on a PSO-LCA calculation, the optimal proportion of S1, S2, S3, S4 and S5 in Xiamen was 9.3%, 0, 35.9%, 28.9% and 25.9%, and these results are consistent with trends in developed countries. At present, the investment for the construction of urban disposal facilities derive mainly from government funding. The result also shows that project viability is highly dependent on the government subsidy. The level of marketization, industrialization and investment efficiency is still low in sludge disposal (Zhang et al., 2016). The low benefit for landfill of sludge disposal further hinder more investors. The sludge-to-resource strategy will also increase the economic feasibility in sludge disposal, which will also attract more private investors.

Based on the results, we present several policy implications which can be generalized to other cities. Future sludge management in Chinese cities should change from the traditional landfill and incineration-dominant pattern to a sludge-to-resource pattern which is more consistent with trends in developed countries. Landfill has higher requirements for sludge dewatering, resulting in negative environmental impacts, and as the large land requirement cannot be ignored the proportion of landfill should be gradually reduced. In future, waste incineration will be the second-best choice in Xiamen, and the incineration capacity is expected to reach 2900 tons/day. Therefore, when the capacity for HPT and compost is limited, using existing incineration facilities can achieve the best trade-off between environmental, economic and social benefits.

The LCA-PSO method enables us to obtain an optimal sludge treatment plan from a given set of alternative feasible strategies based on current disposal capacity in cities, and helps decision makers determine suitable sludge technologies in other rapidly urbanizing areas. The LCA-PSO model developed in this study can be readily applied to other cities, and serves as a useful tool to systematically assess environmental, economic and social performance, thereby facilitating the development of tailored and targeted policies for sustainable sludge management.

7. Discussion

The high water content is an obstacle that affects sludge treatment and disposal (Zhang et al., 2016). The Ministry of Housing and Urban-Rural Development and the Ministry of Environmental Protection have enacted more than ten national and industry standards on sludge disposal. However, there are many problems in the application process (Zhang et al., 2016), and the standard for sludge water content in China is still controversial. The sludge disposal standard for WWTP (GJ3025-1993) regulates the water content of sludge generated from WWTPs to be equal to or less than 80%, and the water content of sludge to landfill has had to be less than 60% since 2007. It is difficult to further dewater sludge without chemical conditioning; as a result, a large amount of landfilled sludge cannot meet the new requirements and is disposed of improperly. In addition, there is still no consensus on the best water content after dewatering. Sludge with 60% water content, rather than 80%, has been proposed as the new standard in view of climate

change effects (Liu et al., 2013). Disposal with a low water content leads to lower CO_2 emissions and human toxicity. However, our results show that when the toxicity resulting from the dewatering process is taken into account, disposal with 60% water content has a higher overall toxicity than disposal with 80% water content. Furthermore, dewatering accounts for about 16%–30% of total cost in the five scenarios. The cost of dewatering to 60% is 54.5% higher than dewatering to 80%. The human toxicity effect and economic performance of the dewatering process cannot be ignored when comparing the different technology routes. We found that 80% water content sludge with HPT had a relatively better environmental performance overall. Reducing the water content of sludge from 96% to 80% results in a lower environmental impact, but reducing the water content further to 60% requires higher material and energy consumption. As a result, the dewatering method and its water content in WWTPs should be determined based on the subsequent disposal process concerning the environmental, social and economic circumstances.

Due to the rapid expansion of cities, the land resource has become an important constraint to the disposal of urban waste. Continuous socio-economic development and the gradual improvement in living standards have caused residents to become more attentive to the quality of the living environment (Wen et al., 2015). From 2009 to 2015, residents in 12 Chinese cities protested against incineration projects due to environmental concerns, and only 3 incineration projects were permitted while the others were cancelled or deferred. In selecting a residential location, people often avoid locations near solid waste and wastewater disposal sites (Deaton and Hoehn, 2004). Social resistance to urban waste disposal sites and WWTPs is often associated with locally undesirable land use patterns (Guidotti and Abercrombie, 2008; Sun et al., 2016). In the long term, the limited capacity of urban landfills and growing 'not in my backyard' campaigns mean that sludge disposal to landfill or incineration plants will become increasingly difficult.

HPT has the lowest consumption of land resources, a relatively small environmental impact and high economic benefits, meaning that it may be the most sustainable future option on technical and public acceptance grounds. Accelerating urbanization, rapid population increases and the expansion of wastewater treatment facilities mean that the quantity of sludge to be disposed of will continue to increase in Chinese cities, and resource utilization will increasingly become the dominant concern. LCA studies reflect the current scientific understanding and data availability of the target system (Yoshida et al., 2013). Future research should focus on the LCA results based on the improvement of HPT under various operating conditions to meet the requirements for minimizing energy/material consumption and maximizing overall biochar production. Biochar provides a promising path for improvement of soil amendment and fertility(Muhammd et al., 2014; Sardar et all, 2013). We still need to strengthen long-term monitoring of the ecological consequences of biochar.

Funding

This work was supported by China-Japanese Research Cooperative Program (2016YFE0118000), Science and Technology Service Network Initiative of the Chinese Academy of Sciences (KFJ-EW-STS-088), Natural Science Foundation of Fujian Province, Grant No. 2015J01177 and 2017J01468.

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